ASSESSMENT OF THE IMPACT OF LIGHT DUTY DIESEL VEHICLES ON SOILING IN CALIFORNIA

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ABSTRACT

The potential soiling cost of increasing the number of light duty diesel vehicles in California is assessed. As used in this report, the term "cost" refers to a total dollar value assigned to a welfare loss. Previous studies of soiling damages from general atmospheric particulate are reviewed and provide a baseline for projecting soiling costs from diesel particulate. A relative soiling impact (soiling index) of diesel particulate compared to average atmospheric particulate is proposed based on the light absorptance and stickiness of diesel particulate. The soiling index and estimates of atmospheric diesel particulate levels associated with a partial dieselization of the light duty vehicle fleet are combined with the general atmospheric particulate soiling costs to obtain soiling cost for diesel particulate.

The soiling cost resulting from a dieselization of 20 percent of the light duty vehicles in California is projected to range from 220 to 2700 million dollars annually depending upon the assigned cost of baseline particulate soiling and the relative soiling impact parameter for diesel particulate. A best estimate annual welfare loss from light duty diesels is 800 million dollars. These figures include only the cost to households. Consideration of costs associated with the soiling of public, commercial, and industrial buildings and their contents and of motor vehicles would further increase the projected costs.

The recent National Research Council (NRC) study on impacts of

diesel-powered light-duty vehicles, as reported in the publication, "Diesel Cars: Benefits, Risks, and Public Policy," does not include potential soiling costs. The inclusion of soiling costs as assessed in the present study alters some of the major conclusions of the NRC study. Uncertainties in estimating soiling costs from diesel vehicles are identified and research which would reduce these uncertainties is suggested.

INTRODUCTION

Concerns for the potential air pollution impact of the increasing number of light-duty diesel vehicles has focused primarily upon particulates, oxides of nitrogen, and odorants. Diesel particulates can adversely affect visibility, soiling, human health, and the physics and chemistry of the atmosphere. Trijonis (1982) recently reviewed the impact of light-duty diesel vehicles on visibility in California. The National Research Council (1982) reviewed the benefits and risks of diselization of the light-duty vehicle fleet, focusing primarily upon potential adverse health effects. Although the issue of soiling is raised and acknowledged in the NRC study, no assessment of the magnitude of this problem or its possible economic impact is provided. The soiling costs of air pollution result from an increased requirement for washing of both interiors and exteriors of buildings, laundering and cleaning of materials, painting of buildings, and washing of motor vehicles. Several studies have been undertaken to estimate the soiling costs of general air pollution (Booz, Allen and Hamilton, 1970; Michelson and Tourin, 1967; Watson and Jaksch, 1980), but little work has been done on the soiling impact of diesel particulate. Because this substance has a high optical absorptance, low density, small size, and is oily in nature, we anticipate that its soiling potential per unit mass is significantly greater than average atmospheric particulate.

The following section reviews previous soiling studies which examine the relationship between atmospheric particulate levels and soiling rates. Also considered are previous estimates of general particulate soiling costs. Subsequently, the nature of diesel particulate is characterized and compared to average atmospheric particulate. An assessment of the soiling cost of diesel particulate from light duty vehicles in California is presented. The consequences of the addition of soiling costs to the NRC study are examined. Finally, uncertainties which could affect the results of the present study are identified and research which would reduce these uncertainties is suggested.

REVIEW OF SOILING STUDIES

The Relation Between Atmospheric Particulate Levels and Soiling

The soiling of exterior building materials was investigated by Beloin and Haynie (1975). They experimentally studied soiling of painted cedar siding, concrete block, brick, asphalt shingles, limestone and window glass. Average atmospheric particulate levels ranged from 60 ug/m3 to 250 ug/m3. Measurements of atmospheric particulate concentrations and soiling of materials were made. For white paints, the soiling (surface reflectance) was found to be directly proportional to the square root of the particle dose (atmospheric particulate concentration times exposure time). Shingle soiling was directly proportional to the particle dose. Good correlations were not found for the other building materials considered.

Michelson and Tourin (1967) related frequency of repainting houses to atmospheric particulate concentrations. Using mailed questionnaires, they surveyed households in the upper Ohio River Valley. The five towns investigated had atmospheric particulate levels ranging from 60 ug/m3 to 235 ug/m3. A linear relationship between repainting frequency and atmospheric particulates was obtained.

Economic Estimates of Soiling Costs

Several economic studies of the dollar cost of soiling have been made. These studies considered general air pollution particulate and did not focus on diesel-emitted particulate. One of the most recent and complete investigations of soiling was performed by Watson and Jaksch (1980). The present work draws extensively from their analysis because they provide a direct estimate of the relation between welfare losses resulting from soiling and atmospheric particulate levels. They establish a welfare loss quantified by the relation between frequency of painting, papering, washing walls and windows, and cleaning venetian blinds and the annual mean suspended particulate level in ug/m3. Costs to governmental, commercial, or industrial facilities were not considered. The cost associated with loss of cleanliness was assumed to be proportional to the atmospheric particulate level raised to an exponent. Exponents were determined from the results of Beloin and Haynie (1975) and Esmen (1973). Finally, Watson and Jaksch calculated the average welfare gain per household from reducing atmospheric particulate. Their results provide the basis for determining soiling costs in the present study. Jaksch (1982) believes that the uncertainties in their cost estimates are such as to underestimate the actual soiling costs. Yu (1978) presented methodology for estimating soiling damage to households. His results yield the percent reduction in soiling costs when atmospheric particulate is reduced but do not provide a quantitative relationship.

Spence and Haynie (1972) assessed the damaging effects of particulate matter on exterior paints. They used the results of Michelson and Tourin (1967) who obtained a linear relationship between frequency of house repainting and atmospheric particulate concentration. The annual United States dollar loss from air pollutants on paints was estimated to 0.5 billion (1967) dollars. The specific cost of paint damage from particulate soiling (separated from total air pollution) was not identified. Studies of the cost of air pollution damage have been conducted by Barret and Wadell (1973) and

Wadell (1974). Although both studies covered a wide range of air pollution costs, including material damage, in neither study is soiling cost identified as a specific item.

ESTIMATION OF RELATIVE SOILING IMPACT OF DIESEL PARTICULATE

Characterization of Diesel Particulate

The optical properties and chemical composition of diesel soot affect the degree of soiling damage. Diesel particulate is about 3.5 times blacker than average urban particulate (Wallin, 1965). Diesel smoke tends to stick to surfaces more than does average particulate.

Wallin (1965) measured the optical reflectance of diesel soot collected on a standard DSIR filter sampling the exhaust of a single cylinder Gardner engine. He compared the reflectance of diesel soot with the known reflectance of average urban particulate. Only 1/3 to 1/4 of the mass of diesel soot compared with urban particulates was required to achieve a stain of equivalent darkness.

Diesel soot is expected to have a greater affinity to surfaces than general atmospheric particulate. General atmospheric particulate is primarily solid matter while diesel soot has both solid and liquid components. The liquid components allow it to adhere to a surface more readily than dry average particulate. Because of its oily component, diesel soot has a greater propensity to smear and is more difficult to remove than dry particulate. The soluble organic fraction (SOF) of diesel soot from light-duty engines varies from 10 to 80 percent by mass, depending on engine operating conditions (Kageyama and Kinehara, 1982). Soluble organic fraction consists of unburned residues of diesel fuel and engine oil. The SOF is usually extracted from soot by the solvent dichloromethane. The remaining soot fraction is dry and consists mainly of carbon. The preceding, qualitative arguments do not appear to have been verified or quantified by experiment.

Soiling Index

The soiling characteristics of diesel soot are much greater than average particulate. As a means of estimating diesel soiling, it is useful to define a "soiling index" which is the ratio of the diesel particulate soiling to average urban particulate soiling on an equal mass basis. The optical properties of diesel soot indicate a soiling index of at least 3 to 4 (Walling, 1965). Stickiness and smearing qualities of diesel particulate (in addition to optical properties) suggest a soiling index of greater than 3 to 4. No data are available which allow quantification of the sticky nature or smearing qualities of diesel particulate. Another uncertainty is the difference, if any, between the deposition characteristics of diesel and average urban particulate. For example, is fine diesel particulate more likely to deposit on vertical walls than larger average urban particulate? Ball (1982) used a soiling index for diesel particulate of 3, based only on its absorptance characteristics. Combining the effects of absorptance and stickiness, our best estimate of a total soiling index is 5. Soiling indices of 2.5, 5.0, and 7.5 are considered to bracket the uncertainty.

ESTIMATION OF SOILING COSTS OF LIGHT-DUTY DIESEL PARTICULATE

Estimates of soiling costs of households as a function of general atmospheric particulate levels have been made by Watson and Jaksch, 1980. These estimates can be utilized to estimate diesel particulate soiling costs. Diesel soiling costs are obtained by utilizing their results and accounting for the additional factors of soiling index, atmospheric diesel particulate levels, and population statistics.

The soiling costs calculation for diesel particulate is outlined in Tables 1-3 for a range of both household cost factors and soiling indexes. California is divided into several regions for convenience of calculation. Diesel particulate levels (column a) are from the results of Trijonis (1982a) who calculated annual average concentrations for 20 percent dieselization of the light-duty vehicle traffic (fraction of light duty vehicle-miles traveled by diesel engine vehicles). Since soiling is a long term, accumulative effect, the annual average is the appropriate concentration. These

Table 1. Annual Soiling Cost Estimation for Light-Duty Diesel Particulate: Low Range, 2.2 (1982 $/household-yr)/(ug/m3 particulate).

	a) Annual-average atmospheric particulate concentration for 20 % dieselization[1]	b) $\frac{\$/(\text{household-yr})}{\mu g/m^3}$ for soiling indexes of:			c) Annual soiling cost per household [$/household-yr] for soiling indexes of:			d) Households	e) Annual soiling costs for light-duty diesels [million $/yr] for soiling indexes of:		
	[$\mu g/m^3$]	2.5	5	7.5	2.5	5.0	7.5	[millions]	2.5	5.0	7.5
Los Angeles area	6 - 9	~5.5	~11	~16	40	80	120	3.54	140	280	420
San Diego area	~5	"	"	"	27	55	80	0.63	17	35	50
Sacramento, Fresno, and Bakersfield area	3 - 6	"	"	"	25	50	75	0.50	13	25	40
San Fransisco Bay area	2 - 4	"	"	"	17	35	50	1.73	30	60	90
Small cities/ rural areas	0.5 - 2	"	"	"	7	14	20	2.43	17	35	50
Total California								8.83	~220	~450	~650

Note: All costs in June 1982 dollars

[1] Trijonis (1982)

Table 2. Annual Soiling Cost Estimation for Light-Duty Diesel Particulate: Intermediate Range, 3.9 (1982 \$/household-yr)/(ug/m3 particulate).

	a) Annual-average atmospheric particulate concentration for 20 % dieselization[1]	b) \$/(household-yr) / $\mu g/m^3$ for soiling indexes of:			c) Annual soiling cost per household [\$/household-yr] for soiling indexes of:			d) Households [millions]	e) Annual soiling costs for light-duty diesels [million \$/yr] for soiling indexes of:		
	[$\mu g/m^3$]	2.5	5	7.5	2.5	5.0	7.5		2.5	5.0	7.5
Los Angeles area	6 - 9	~10	~20	~30	75	150	220	3.54	270	530	780
San Diego area	~5	"	"	"	50	100	150	0.63	30	65	95
Sacramento, Fresno, and Bakersfield area	3 - 6	"	"	"	45	90	140	0.50	22	45	70
San Fransisco Bay area	2 - 4	"	"	"	30	60	90	1.73	50	100	160
Small cities/ rural areas	0.5 - 2	"	"	"	12	25	38	2.43	29	60	90
Total California								8.83	~400	~800	~1200

Note: All costs in June 1982 dollars

[1] Trijonis (1982)

Table 3. Annual Soiling Cost Estimation for Light-Duty Diesel Particulate: High Range, 8.7 (1982 \$/household-yr)/(ug/m3 particulate).

	a) Annual-average atmospheric particulate concentration for 20 % dieselization[1]	b) \$/(household-yr) / $\mu g/m^3$ for soiling indexes of:			c) Annual soiling cost per household [\$/household-yr] for soiling indexes of:			d) Households [millions]	e) Annual soiling costs for light-duty diesels [million \$/yr] for soiling indexes of:		
	[$\mu g/m^3$]	2.5	5	7.5	2.5	5.0	7.5		2.5	5.0	7.5
Los Angeles area	6 - 9	~22	~45	~65	170	340	500	3.54	600	1200	1800
San Diego area	~5	"	"	"	110	220	330	0.63	70	140	210
Sacramento, Fresno, and Bakersfield area	3 - 6	"	"	"	100	200	300	0.50	50	100	150
San Fransisco Bay area	2 - 4	"	"	"	65	130	200	1.73	110	220	330
Small cities/ rural areas	0.5 - 2	"	"	"	27	55	80	2.43	65	130	200
Total California								8.83	~900	~1800	~2700

Note: All costs in June 1982 dollars

[1] Trijonis (1982)

particulate levels are approximately linear with percent dieselization (Trijonis, 1982b). The concentrations reported by Trijonis (1982a) were multiplied by 4/3 to yield the total particulate level from the elemental carbon level (diesel particulate is about 3/4 elemental carbon) and multiplied by 0.8 to correct his lead-tracer model for lead from medium and heavy duty vehicles (Trijonis, 1982b).

A ratio of household soiling costs to particulate levels is given in the adjacent column b). This ratio, as used in Tables 1-3, is derived from Table 3 of Watson and Jaksch (1980) where they reported the welfare gain per household if the general atmospheric particulate levels were reduced from the primary air quality standard of 75 ug/m3 to the secondary air quality standard of 60 ug/m3. From their results, the ratio of incremental soiling costs to incremental particulate levels for average urban particulate was calculated as follows:

$$\left[\frac{(70 - 41)\ \ (1971\ \$/\text{household-yr})}{(75 - 60)\ \ \ \ (\text{ug/m3})}\right]\left[2.04\ \frac{(1982\ \$)}{(1971\ \$)}\right]$$

giving 3.9 (1982 \$/household-yr)/(ug/m3 particulate) for Table 2 (intermediate range). Values of 2.2, 3.9, and 8.7 (1982 \$/household-yr)/(ug/m3 particulate) were arbitrarily selected to bracket the uncertainty in their results and represent the "low range," "intermediate range," and "high range" identified in Tables 1, 2, and 3 respectively. The effect of inflation of the dollar from 1971 to June 1982 (2.04), was determined from the consumer price index (U.S. Bureau of Labor Statistics, 1982 and U.S. Bureau of the Census, 1981). The ratio of soiling costs to particulate level was multiplied by soiling indices of 2.5, 5.0, and 7.5 to yield the values in Tables 1-3. The product of column a) and column b) gives column c), the diesel soiling cost per household-year.

The U.S. Bureau of Census (1982) in its report of the 1980 census provides populations of urbanized areas listed in Tables 1-3. The number of persons per household is required to calculate the number of households for each region. The Statistical Abstract of the United States (1981) in Table 63 reports the number of persons per household in California as 2.68 which is used to calculate the number of households in the various regions. Population not accounted for in one of the urban areas is assigned to "small cities/rural areas." The final results in column e) are simply the product of the number of households, column d) and the soiling cost per household-year, column c).

For 20 percent dieselization of the light-duty vehicle traffic, the best estimate of the annual cost to California households resulting from light-duty diesel soiling is 800 million dollars. This cost is approximately linear with percent dieselization. Lower and upper brackets on this cost resulting from possible uncertainties in the household soiling cost and soiling index numbers are 220 and 2700 million dollars. Neglected costs associated with public, commercial, and industrial facilities and transportation vehicles suggest that actual costs are more likely to be greater than the 800 million dollars best estimate than lower.

EFFECT OF SOILING COSTS ON NATIONAL RESEARCH COUNCIL CONCLUSIONS

Part of the National Research Council study on the impacts of diesel-powered light duty vehicles treats the costs and benefits of changing the light duty diesel particulate emission standard from 0.6 g/mi to 0.2 g/mi. The results of nine cases are summarized in Table 7.4 of the report "Diesel Cars: Benefits, Risks, and Public Policy," NRC (1982) which is reproduced as Table 4 of this report. These cases cover a range of consumer responses (diesel vehicle sales) resulting from the imposition of the 0.2 g/mi particulate emission standards. The effects of the more stringent standards are quantified in terms of a range of values for benefits associated with A) cancer reduction and B) visibility improvement and costs associated with C) safety reduction, D) import reduction premium (the societal value of not importing oil), and E) increased user costs. Combinations of effects are selected to provide cases most favorable to a 0.2 gm/mi standard, intermediate cases, and cases most favorable to 0.6 g/mi. The effects are aggregated in terms of a net resource gain (loss) associated with items B) through E) above. Cancer reduction is assessed in person-years saved but a benefit for reduced treatment costs or for the value of the person-years saved is not included. That is, the only resource (dollar) benefit appearing in this accounting is that associated with visibility improvement. All cases considered, which should include the extreme possibilities, show a net United States resource loss in 1995. These losses

Table 4. Benefits and Costs in 1995 from Changing Particulate Standard for 0.6 g/mi to 0.2 g/mi (Table 7.4, National Research Council, 1982).

	Cases Most Favorable to 0.2 g/mi Set A			Intermediate Cases Set B			Most Favorable to 0.6 g/mi Set C		
	A1	A2	A3	B1	B2	B3	C1	C2	C3
Benefits:									
A. Cancer Reduction (Person-years saved)	36,000	46,000	46,000	2,400	3,100	3,100	0	0	0
B. Visibility Improvement (10^6 dollars)	280	360	360	130	170	170	0	0	0
Costs:									
C. Safety Reduction (Person-years lost)	0	11,000	0	0	22,000	0	0	45,000	0
D. Import Reduction Premium (10^6 dollars)	0	0	170	0	0	430	0	0	850
E. Increased User Costs (10^6 dollars)	560	390	390	1,500	1,040	1,040	2,250	1,550	1,550
Summary:									
F. Person-Years Saved (Lost)	36,000	35,000	46,000	2,400	(18,900)	3,100	0	(45,000)	0
G. Resource Gain (Loss) (10^6 dollars)	(280)	(30)	(200)	(1,370)	(870)	(1,300)	(2,250)	(1,550)	(2,400)
H. Resource Loss Per Person-Year Saved (in dollars)	7,800	860	4,300	571,000	--	419,000	--	--	--

In most cases these values can be derived straightforwardly from the assumptions of Table 7.3 (with adjustments for rounding). Examples drawn from Case A illustrate the method. The way of deriving the Summary figures is also given.

$A = d \times e$ $36{,}000 = 140 \times 255$

$B = d \times f$ $280 = 140 \times 2022$

$C = c \times g$ $11{,}000 = 75 \times 150$

$D = h \times i$ $170 = .10 \times 1700$

$E = a \times j$ $560 = 29.5 \times 19$

$F = A - C$

$G = B - D - E$

$H = - G/F$

range from 30 to 2400 million dollars. The limited and somewhat arbitrary benefits and costs included would appear to be a major deficiency of the analytical model of this study. The benefits of reduction of soiling, morbidity, and mortality are some possible important omissions.

The impact of including the benefits of soiling reduction on the NRC cost-benefit analysis can be examined by adding a new benefit to NRC Table 7.4. We caution that inclusion of soiling costs alone does not correct the deficiencies of the NRC analytical model. The conclusions resulting from this exercise simply point to the importance of soiling and should not be taken as thorough assessment of the benefits and costs of control of diesel particulate. If the average US increase in particulate from 25% dieselization, the NRC base case, is taken to be 3 ug/m3 (this is an estimate but consistent with Table 3.1 of the NRC report and with values used in the present report), the reduction in ambient diesel particulate resulting from going from a .6 g/mi to .2 g/mi emissions standard is then 2 ug/m3. Combining this reduction with our intermediate household welfare loss of 20 ($/household-yr)/(ug diesel particulate/m3) and an estimated 70 million households in the United States gives an annual benefit of 2800 million dollars. This result is best compared with NRC case "B1". The inclusion of the benefit of reduced soiling changes the reported national annual resource loss of 1370 million dollars into a resource gain of 1430 million dollars.

A major conclusion of the NRC study comes from the "regrets analysis" (pages 124-126). In this part of the analytical study, value is assigned to the benefits from saved person-years resulting from reduced cancer incidence.

It is concluded, Table 7.6, that the cost of choosing a 0.6 g/mi particulate standard and having all of the uncertainties prove to favor a 0.2 g/mi standard is much less than choosing a 0.2 g/mi particulate standard and having all of the uncertainties prove to favor a 0.6 g/mi standard. If soiling costs had been included and the same methodology applied, this conclusion would have been reversed (although the regrets costs would be substantial in both cases).

UNCERTAINTIES AND RESEARCH NEEDS

The two major uncertainties which will affect the outcome of this study are the household costs of soiling per unit of atmospheric particulate concentration and the soiling index. It should be noted that the Watson and Jaksch (1982) study deals with a specific reduction from 75 to 60 ug/m3 in atmsopheric particulate. This level is not necessarily characteristic of all areas of California. Also note that a linear extrapolation to further reductions would suggest that there is a level of atmospheric particulate below which further reduction would produce no savings. This means either that the linear relation which is implied in their study and used in this report is incorrect or, indeed, that there is an intercept. That is, household cleaning costs would fall to zero at some finite level of ambient particulate--an unlikely event. Use of their results presumes a cause-effect relationship between changes in atmospheric particulates and changes in household soiling costs. Other air pollutants may play a role, for example gaseous sulfur dioxide, and particulate could be a surrogate indicator of such species. It seems likely that particulate, rather than gaseous air pollutants dominates soiling. Additional surveys, in California, to establish the relationship between atmspheric particulate levels and soiling costs could provide data more directly related to the California situation. Obtaining data adequate to establish the nature of the non-linearity between particulate levels and soiling costs would be difficult.

Relative absorptance, stickiness, and deposition characteristics are particulate properties which are important in establishing the soiling index. A direct determination of a soiling index might be obtained by exposing painted surfaces and materials to diesel particulate free air, average particulate containing air, and diesel particulate containing air, each with a range of particulate concentrations. The difficulty of restoring the surface or materials through painting or washing could then be quantified and a soiling index thereby assigned. A method for determining the fraction of ambient particulate which is diesel particulate would be a useful tool but remains to be developed.

Further refinements to the present study could include the impact of medium and heavy duty vehicles, a more refined geographical grid, and projections based on the range of diesel particulate emission standards now scheduled for California and diesel vehicle sales. The cost to the soiling of governmental, commercial, and industrial facilities and to transportation vehicles should also be investigated.

MAJOR CONCLUSIONS

Major conclusions resulting from this study are:

1) Diesel particulate is dirtier than average atmospheric particulate. The relative soiling index is estimated to be five.

2) Increasing dieselization of the light duty vehicle fleet in California carries with it substantial soiling costs. For 20 percent light duty diesel vehicle traffic, the soiling costs to households are estimated to be between 220 and 2700 million dollars annually. Imposition of the scheduled particulate emission standards would reduce these costs.

3) Consideration of soiling from medium and heavy duty vehicles and the impact upon facilities other than households and upon transportation vehicles will further increase costs.

4) The inclusion of soiling costs alters some of the major conclusions of the recent National Research Council study, Impacts of Diesel-Powered Light-Duty Vehicles. Results which disfavor going from a 0.6 g/mi to a 0.2 g/mi particulate emission standard are reversed if soiling costs are included.

5) Relatively high uncertainties in quantification of soiling costs from diesel particulates result from the difficulty of assigning the soiling cost of particulates in general and the relative soiling characteristics of diesel particulate. Some of the uncertainty in the first, especially in application to California, might be reduced by additional surveys. The soiling index could be placed on a firm quantitative basis by relatively simple experiments.

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